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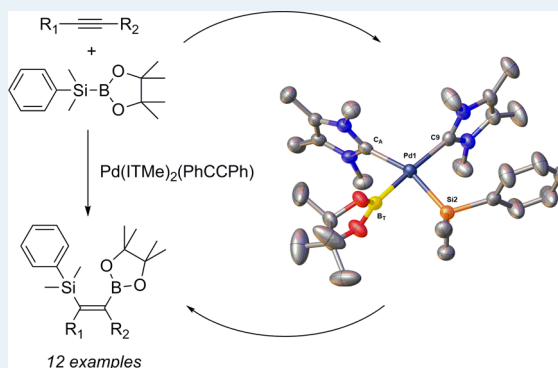
(N-Heterocyclic Carbene)₂-Pd(0)-Catalyzed Silaboration of Internal and Terminal Alkynes: Scope and Mechanistic Studies

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S Supporting Information

ABSTRACT: Pd(ITMe)₂(PhC≡CPh) acts as a highly reactive precatalyst in the silaboration of terminal and internal alkynes to yield a number of known and novel 1-silyl-2-boryl alkenes. Unprecedented mild reaction temperatures for terminal alkynes, short reaction times, and low catalytic loadings are reported. During mechanistic studies, *cis*-Pd(ITMe)₂(SiMe₂Ph)(Bpin) was directly synthesized by oxidative addition of PhMe₂SiBpin to Pd(ITMe)₂(PhC≡CPh). This represents a very rare example of a (silyl)(boryl)palladium complex. A plausible catalyst decomposition route was also examined.

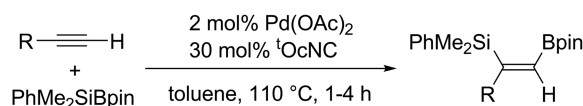


KEYWORDS: N-heterocyclic carbene, silaboration, homogeneous catalysis, alkyne, palladium, synthetic methods

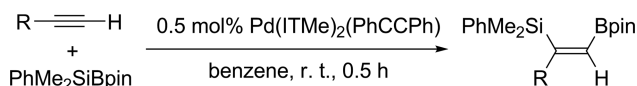
The regio- and stereoselective synthesis of multisubstituted alkenes is a challenging reaction, recurrent in the formation of complex organic structures. In particular, tri- and tetra-substituted alkenes are present in many pharmaceuticals,¹ dipeptide mimetics,² polymers,³ and columnar liquid crystals.⁴ There are now many reported methods for the synthesis of such alkenes including olefin metathesis⁵ and carbonyl olefination,⁶ among others.⁷ Notably, the transition-metal catalyzed π -insertion of a bond between two elements of the p-block (e.g., Si–Si, Si–Sn, Sn–Sn, B–B, and Si–B) into an alkyne has received a significant amount of attention.⁸ One of the most interesting examples is arguably the 1,2-addition of a silicon–boron bond (silaboration).⁹ The resulting 1-silyl-2-boryl alkenes have the potential to independently undergo, for example, a cross-coupling reaction at the boryl (Suzuki–Miyaura) fragment¹⁰ and a Fleming–Tamao oxidative addition or cross coupling (Hiyama) at the silyl fragment.^{11,12} Arguably, the most effective alkyne silaboration protocol is the palladium diacetate/isocyanide combination reported by Ito and co-workers (Scheme 1).^{13,14} The reactions proceed with high stereoselectivity toward the *syn*-1,2-addition products and in the case of terminal alkynes high regioselectivity, with the boryl fragment attached to the terminal position. Recently, Suginome and co-workers reported that the reverse regioselectivity was possible by changing the palladium source and using a sterically encumbered phosphine ligand, albeit using the more reactive (chlorodimethylsilyl)boronic acid pinacol ester.¹⁵ “Abnormal” regioselectivity was also reported by Stratakis and co-workers using a supported gold nanoparticle catalyst.¹⁶ However, alkyne silaboration protocols have been largely limited to high reaction temperatures, long reaction times, and moderately high catalyst loadings. The most challenging aspect to silaboration chemistry

Scheme 1. Silaboration of Terminal Alkynes

Ito and co-workers: best general protocol to date



this work:



remains the silaboration of unsymmetrical internal alkynes and the resulting formation of regioisomeric mixtures; there are limited examples that remedy this.^{13b,17,18}

N-Heterocyclic carbenes (NHCs) have replaced phosphines in many catalytic reactions. They are known to exhibit equivalent or better σ -donor character than the most common phosphines, and the resulting (NHC)-M complexes are also often more robust toward decomposition.¹⁹ We recently reported the use of NHCs as a set of ligands in the first isolation of a bis(trimethylsilyl)palladium complex, *cis*-Pd(ITMe)₂(SiMe₃)₂ (ITMe = 1,3,4,5-tetramethylimidazol-2-ylidene) and the first example of a bis(NHC)-palladium alkyne complex, Pd(ITMe)₂(PhC≡CPh) (**1**).²⁰ Both complexes acted as highly active precatalysts for the *cis*-bis-silylation of

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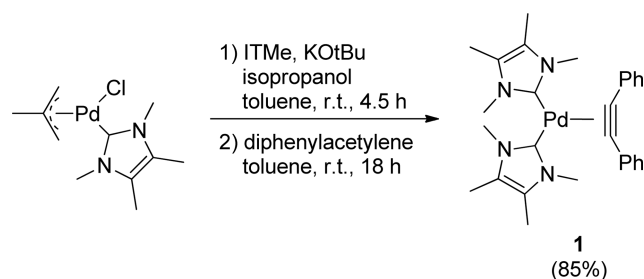
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sterically and electronically demanding internal and terminal alkynes. The high reactivity exhibited by **1** prompted us to investigate its effectiveness at catalyzing the silaboration of alkynes. Herein, we report the use of $\text{Pd}(\text{ITMe})_2(\text{PhC}\equiv\text{CPh})$ in the silaboration of sterically and electronically demanding terminal and symmetrical internal alkynes. Unprecedented low catalytic loadings, short reactions times, and mild reaction temperatures for terminal alkynes are presented. Initial experimental investigations into the mechanism of the reaction and the isolation of important intermediates are also described.

We had previously synthesized $\text{Pd}(\text{ITMe})_2(\text{PhC}\equiv\text{CPh})$ (**1**) in what was effectively a three-step process.²⁰ We have since devised an improved synthesis of **1**: $\text{Pd}(\text{ITMe})(\text{methallyl})\text{Cl}$ was reacted with one equivalent of each of potassium *tert*-butoxide, isopropanol, and ITMe at room temperature forming $\text{Pd}(\text{ITMe})_2$, which was then exposed *in situ* to a slight excess of diphenylacetylene at room temperature for 18 h in toluene. After workup, **1** was isolated in an 85% yield (Scheme 2).

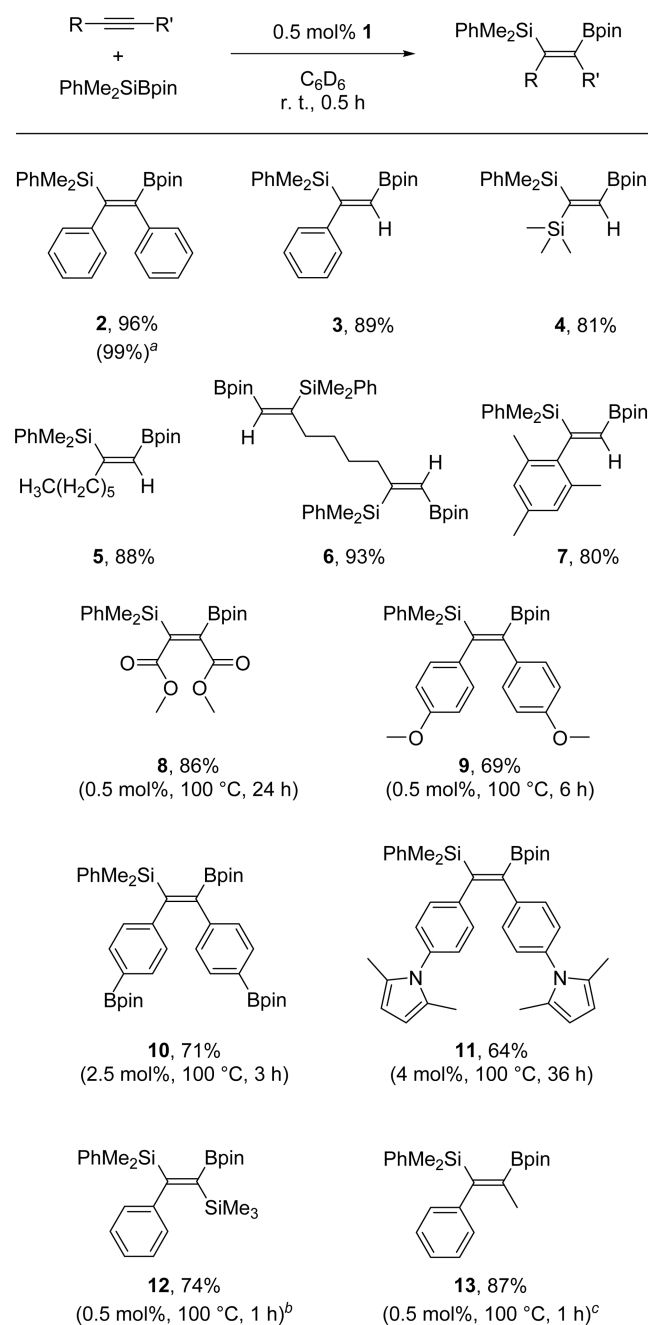
Scheme 2. Improved Synthesis of **1**



With large quantities of **1** in hand, we proceeded to investigate its capacity to catalyze the silaboration of alkynes. Diphenylacetylene and (dimethylphenyl)silyl boronic acid pinacol ester ($\text{PhMe}_2\text{SiBpin}$) were chosen as model substrates for the optimization of the initial reaction parameters. The reaction was carried out in C_6D_6 in order to monitor its progression. To our delight, (*E*)-(1,2-diphenyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)vinyl)dimethyl(phenyl)silane (**2**) was obtained in 96% yield (100% stereoselectivity) using 0.5 mol % of **1** at room temperature and in less than 30 min (Scheme 3). A comparable yield was obtained in benzene. The only report for a catalytic synthesis of this compound required 2 mol % of $\text{Pd}(\text{OAc})_2/30$ mol % *tert*-octyl isocyanide at 110 °C over 2 h.^{13b} To scope the versatility of this protocol, a series of sterically and electronically challenging alkynes were reacted with $\text{PhMe}_2\text{SiBpin}$. The silaboration of terminal aryl, alkyl, silyl, and even diterminal alkynes proceeded at room temperature using 0.5 mol % of **1** in less than 30 min with 100% regio- and stereoselectivity. As for compound **2**, the only previous synthesis of compounds **3–6** required 2 mol % of $\text{Pd}(\text{OAc})_2/30$ mol % *tert*-octyl isocyanide at 110 °C, in reaction times varying from 1 to 4 h,^{13b} whereas compound **7** has not been previously reported, to the best of our knowledge.

There are only a few examples of catalytic silaborations of symmetrical and unsymmetrical internal alkynes in the literature: namely, Ito and co-workers' silaboration of diphenylacetylene, 1-phenyl-1-propyne and dec-5-yne,^{13b} Sawamura and co-workers' organocatalytic silaboration of polar-coordinating internal alkynes,¹⁷ and Sato and co-workers' ynamide silaboration.¹⁸ Mixtures of regioisomers are usually observed in the silaboration of unsymmetrical internal alkynes. However, to our knowledge, a more thorough investigation into

Scheme 3. Silaboration of Terminal and Internal Alkynes



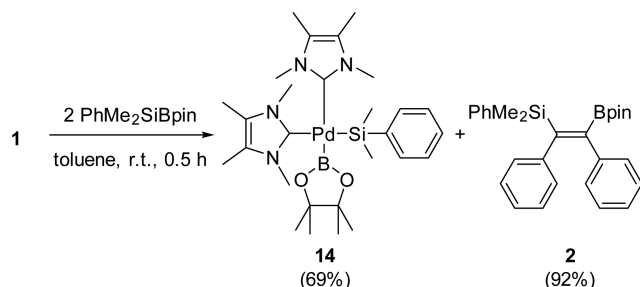
^aYield in C_6H_6 under same reaction conditions; ^bMajor isomer isolated from a mixture that included 20% of the other regioisomer; ^cMajor isomer isolated from a mixture that included 7% of the other regioisomer.

the silaboration of symmetrical alkynes that are electronically challenging has not been reported. Albeit requiring temperatures of 100 °C, the novel compounds **8–11** were all synthesized with 100% *cis*-stereoselectivity as established by NOESY NMR. Both alkyl–alkyl and aryl–aryl internal alkynes bearing functionalities such as carboxylic ester, boronate ester, pyrrole, and ether reacted well under these conditions. Two unsymmetrical alkynes were also subjected to these reaction conditions. The silaboration of 1-phenyl-1-propyne afforded compound **13**, isolated as the major regioisomer of a mixture containing 7% of the other regioisomer. This is a similar result

to that obtained by Ito,^{13b} albeit in a shorter reaction time and using a lower catalyst loading. On the other hand, the silaboration of unsymmetrical alkyne 1-phenyl-2-trimethylsilylacetylene resulted in the isolation of the novel compound **12** as a major product from an 80:20 mixture of regioisomers.

We then turned our attention to the mechanism of these reactions. The proposed catalytic cycle for “normal” silaboration using Pt group catalysts involves an initial oxidative addition resulting in a *cis*-(silyl)(boryl)M(II) complex. The alkyne then undergoes migratory insertion into the M–B bond to form the corresponding (silyl)-M^{II}-(borylvinyl) species, followed by a reductive elimination to form the 1-silyl-2-boryl-alkene.²¹ The isolation of the oxidative addition products for Pt group complexes is extremely rare due to their low stability: to our knowledge, the only reported examples to date are a series of (phosphine)-Pt complexes reported by Ozawa and co-workers^{21a} and one Pd complex reported by Onozawa and Tanaka.²² We decided to investigate the stoichiometric reactivity of **1** in the hope of isolating this important intermediate in the catalytic cycle. On reacting two equivalents of PhMe₂SiBpin with **1** in toluene, *cis*-Pd(ITMe)₂(SiMe₂Ph)(Bpin) (**14**) and **2** formed at room temperature in under 30 min. (Scheme 4). Single crystals of **14** were isolated from a

Scheme 4. Synthesis of Compounds **14** and **2**



double recrystallization in acetonitrile at –30 °C. X-ray analysis indicated a distorted square planar geometry with the NHCs orthogonal to the Si–Pd–B plane (Figure 1). To gain further insights on the reactivity of **14**, we carried out its stoichiometric reaction with diphenylacetylene, leading to the quantitative formation of **1** and **2** at room temperature in only 10 min (see Supporting Information). Unfortunately, attempts of isolating the borylvinyl-Pd-silyl intermediate generated after the migratory insertion step were unsuccessful.

Complex **14** seems indefinitely stable to decomposition as a solid under inert conditions. It however rapidly decomposes in solution in nonpolar aromatic solvents such as toluene and benzene and at a slower rate in acetonitrile. By monitoring the mixture in C₆D₆ by ¹H NMR, we assigned the decomposition products as Pd(ITMe)₂, B₂pin₂, palladium black and an unknown (NHC)-Pd complex, which we tentatively identified as *cis*-Pd(ITMe)₂(SiMe₂Ph)₂ (**15**) (Scheme 5). The identity of **15** was confirmed by an independent synthesis, reacting Pd(ITMe)₂ and 1,1,2,2-tetramethyl-1,2-diphenyldisilane (PhMe₂SiSiMe₂Ph). Single crystals of **15** were isolated from a saturated solution of toluene/benzene (10:1) at room temperature (see Supporting Information).^{20,23} This decomposition of **14** in solution leading to Pd black could very well explain catalyst death with time as the concentration of the alkyne in solution decreases.

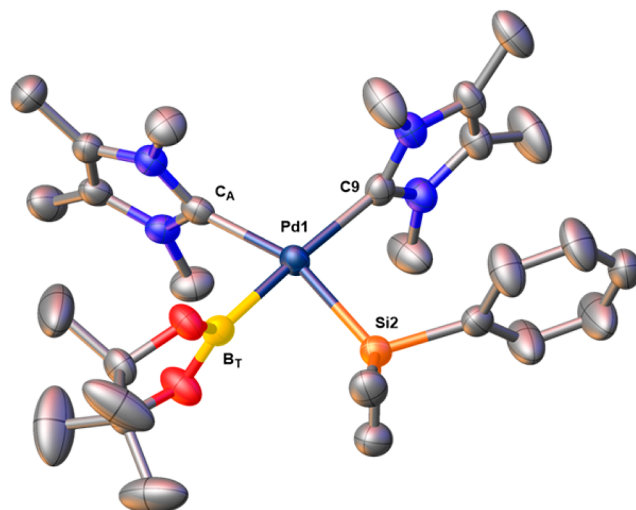
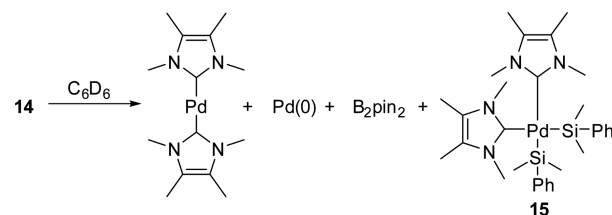


Figure 1. Molecular structure of **14** with thermal ellipsoids at the 50% probability level. Hydrogen atoms are omitted for clarity. Selected bond lengths [Å] and angles [°]: Pd1–C_A: 2.091(3), Pd1–C₉: 2.120(3), Pd1–B_T: 2.038(4), Pd1–Si2: 2.3352(9), C_A–Pd1–C₉: 103.26(12), C₉Pd1–Si2: 94.71(9), B_T–Pd1–Si2: 81.49(11), C_A–Pd1–B_T: 80.89(13).

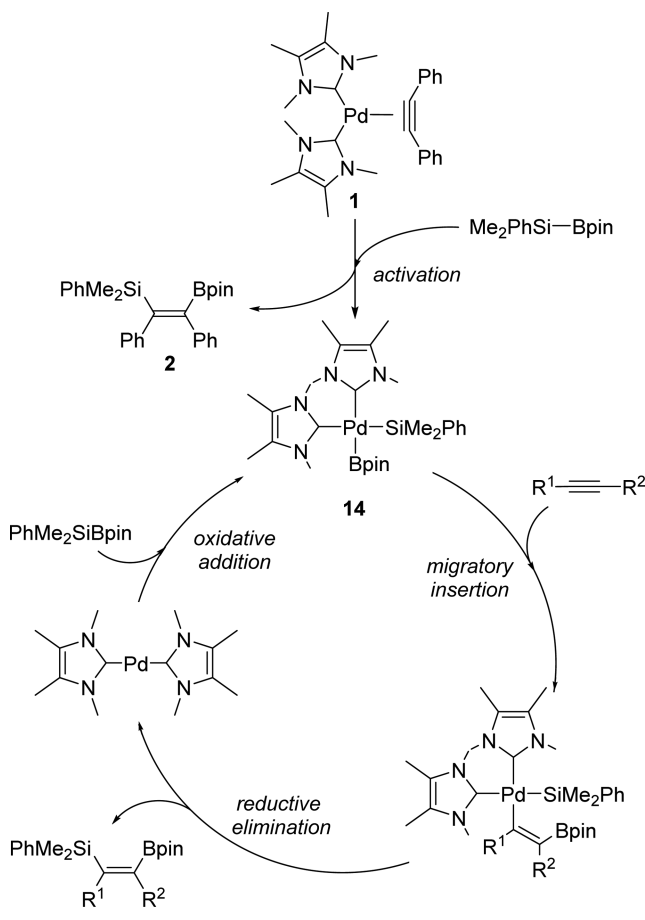
Scheme 5. Decomposition of **14** in Solution



With all this information in hand, we propose the mechanism depicted in Scheme 6, starting with the activation of complex **1** leading to the formation of complex **14**, as shown in our mechanistic studies. We then suggest the approach of the alkyne above the plane of the molecule because, due to their nature, it is unlikely that neither the NHCs, silyl nor boryl groups would detach prior the coordination of the alkyne. A subsequent migratory insertion of the boryl group into the alkyne would then form a borylvinyl–palladium–silyl intermediate. This preferred boryl migration over silyl migration has been thoroughly investigated in the literature and is believed to be both a kinetically and thermodynamically favorable process.^{21,24} A weak coordination of the boryl moiety to the Pd center would stabilize the borylvinyl palladium intermediate and allow for a stereoselective reductive elimination,²⁵ generating the desired silaborated product and 14 e[–] complex Pd(ITMe)₂, the catalytically active species in the cycle.

In conclusion, we have shown that complex **1** is a very reactive precatalyst in the silaboration of sterically and electronically demanding internal and terminal alkynes, proceeding at much lower catalyst loadings, milder temperatures (in the case of terminal alkynes), and in much faster reaction times than in previous protocols reported in the literature. Investigations into the mechanism for this reaction resulted in synthesis of *cis*-Pd(ITMe)₂(SiMe₂Ph)(Bpin). This represents a very rare example of a (silyl)(boryl)palladium complex isolated from the oxidative addition of a Si–B reagent to a Pd(0) center. Studies into the catalytic potential of **1** in

Scheme 6. Proposed Catalytic Cycle



other challenging bond activations are currently ongoing in our laboratories.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acscatal.6b00127.

X-ray data (CIF)

X-ray data (CIF)

X-ray data (CIF)

Experimental procedures, characterization data for all compounds, and NMR spectra (PDF)

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Notes

The authors declare no competing financial interest.

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